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Published in:
Robot and Human Interactive Communication (RO-MAN)

DOI:
10.1109/ROMAN.2016.7745205

Publication date:
2016

Citation for published version (APA):
Beckerle, P., De Beir, A., Schürmann, T., & Caspar, E. (2016). Human body schema exploration: Analyzing design requirements of Robotic Hand and Leg Illusions. In *Robot and Human Interactive Communication (RO-MAN)* (pp. 763-768). IEEE. https://doi.org/10.1109/ROMAN.2016.7745205

25th IEEE International Symposium on
Robot and Human Interactive Communication (RO-MAN)
August 26-31, 2016. Columbia University, NY, USA

Human body schema exploration: analyzing design requirements of robotic hand and leg illusions*

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Abstract— **Understanding the integration of user-proximal robots in the body schema of their human users has a distinct potential to improve human-robot interaction. Robotic devices can help to investigate the psychological fundamentals of body schema integration. While the Rubber Hand Illusion experiment indicates how artifacts can be perceived as a part of the own body, it relies on a passive limb that does not perform motions during the examinations. Novel setups aim at Robotic Hand/Leg Illusions induced by robotic devices which imitate human motions. Although such devices distinctly extend experimental possibilities, their design is rather proprietary and unstructured up to now. This paper analyzes the requirements of robotic hand and leg illusion setups based on systematic discussion of a multidisciplinary team of researchers from engineering and psychology. In a comparative study, requirements are collected and structured, their similarities and differences are determined, and the most important ones are extracted yielding design implications. The requirements with the highest priority are setup characteristics that concern the occurrence and quality of the illusion, i.e., hiding the real limb, anatomical plausibility, visual appearance, temporal delay, and software-controlled experimental conditions. Based on the results, the design of future robotic devices for the exploration of human body schema integration might be guided and supported.**

I. INTRODUCTION

Human body schema describes the representation of the characteristics of own's body in a subconscious, neurophysiological, and multisensory way [1], [2]. It seems to be kind of an internal model of the body mechanics that might integrate robot limbs similarly to tools in general [3], [4], [5], [6]. To study this phenomenon, the Rubber Hand Illusion (RHI) paradigm is very promising: a synchronous stimulation of the subject's hidden real hand and of a visible rubber hand induces a feeling of body-ownership regarding the latter one [7]. Since the seminal paper on the RHI [7], various research has been conducted considering the hand and other limbs [8], [9], [10], even the whole body [11], [12], [13].

Although RHI and its potential applications are very promising, the underlying mechanisms are still not completely understood: studies indicate that perceptual and neuronal stability of the illusions depends on temporal and spatial factors such as the experimental setup [14]. Various studies report that illusory embodiment can be caused and stabilized by multisensory integration of visual, tactile, motor, and proprioceptive information [15], [16], [17].

This relates them to robotics where factors supporting body schema integration might yield design objectives for human-robot interaction and interfaces, e.g., temporal, spatial, or feedback [18], [19] issues. To explore potentials and open issues, new methods to explore such illusions such as robotic limbs and virtual reality technologies have been developed to study body schema integration regarding the limbs [20], [16], [21], [22], [23], [24], [19], [25]. The corresponding illusions are referred to as robotic hand/leg illusion (RobHI/RobLI) [22], [26] or virtual hand/leg illusion [16], [27]. Using such human-in-the-loop experiments offers several advantageous possibilities: influences on body experience can be simulated very precisely, e.g., in terms of delays [16], and stimulation becomes variable, e.g., randomly moving another finger of the robotic hand [21], [24]. Since the robotic devices are mimicking human motions, those are referred to as active paradigms.

Yet, limitations might be caused by the technical implementation, e.g., due to design-related delays [28], [22]. Beyond yielding benefits in experimenting, designing human-in-the-loop simulators can indicate requirements itself. Since those are similarly important for the final robotic applications, they can later be reused to design those, e.g., as delay thresholds or size limitations [29]. Additionally, such robotic devices facilitate to examine how human-robot interfaces might improve body schema integration [19]. The main objectives of this paper are: 1) to analyze robotic setups for the experimental investigation of limb body schema integration, 2) to identify similarities and differences of their design requirements, and 3) to prepare implications for the development of such systems.

The concepts of existing robotic setups that are used for RobHI and RobLI experiments are presented and their technical implementations are described in Section II. Subsequently, Section III gives an analysis of the design requirements extracted from publications about the considered setups and referring to additional literature on the underlying effects. Similarities and differences between RobHI and RobLI are determined and requirement importance is investigated. The identified requirements are discussed and design implications are given based on this analysis in Section IV. The results are further interpreted and assessed from a psychological perspective. A conclusion of the insights and potential design procedures is presented in Section V.

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II. ROBOTIC APPROACHES

The rubber hand illusion was initially described by Botvinick and Cohen [7] and has been widely used in psychology to study the sense of body-ownership, i.e., our feeling that our body parts belong to us. Since then, an active paradigm has been proposed and realized by introducing rigid connections of human and fake hands [30], [31]. The interest of this active paradigm is that participants experience a sense of body-ownership and an additional sense of control with respect to the fake hand, i.e., agency. This active paradigm has been used to study the relationship between the sense of body-ownership and the one of agency. As described in Section I, the active paradigm can be extended using robotic limbs, i.e., hands, legs, etc. The basic concepts of the corresponding robotic devices are explained subsequently.

A. *Robotic Hand Illusion*

Caspar et al. proposed to use a robotic hand rather than a fake rubber hand to investigate the relationship of body-ownership and agency [21]. This approach offers several advantages compared to using a rubber hand. First, delays between the real and the fake hand are better controlled. Previous studies reported asynchronous conditions in which the fake hand was moved by the experimenter with an approximate delay of 500 ms. The delay was indeed approximate because the experimenter tried to pull a cord attached to the finger of the fake hand with a delay of 500 ms after the participants movement, making the procedure rather imprecise. With the robotic device, the exact delay that breaks the illusion can be determined. Such results can provide insights towards long-term prosthetic integration, e.g., a maximum delay between volition and prosthetic motion.

Another advantage associated with this device is the possibility to create different finger mappings. While previous studies are limited in this option because of the thin wooden rob that has to link the real and the fake fingers, the robotic hand allows to rapidly switch the congruence of the mappings between the different fingers.

The RobHI setup was also used for fundamental research on volition and agency [24]. Such fundamental research is a key towards a better understanding of long-term prosthetic integration. Recently, a comparison between the classical visuo-tactile illusion and the active visuo-motor illusion has shown that, although both illusion had similar intensity, the active illusion is established faster. This suggests that the design of prosthetic should be more concerned by motion delays than by tactile feedback. Such effects show that experimental insights can guide engineers to order design issues regarding their importance.

Fig. 1. Setup of RobHI as proposed in [22].

The RobHI setup consists of a low-cost 3D printed robotic hand and a sensor glove that tracks subject finger flexion. Real hand and glove are hidden under a table as shown in Figure 1. Contrary to robotic hands that are generally available on the market and focus on grasping, this robotic hand was designed focusing on human like shape and fast fingers motion. A program controlled via Psychotoolbox allows to switch finger mapping or delays during the experiment to create unexpected conditions for the participants.

B. *Robotic Leg Illusion*

Beckerle et al. suggested a robotic leg to explore lower limb body schema integration [25]. By including motions, insights in artifact integration can support user-proximal robot design and control. Therefore, re-configurable and reproducible delays between human and robotic leg help determining thresholds. Further issues are the investigation of the visuo-motor illusion and tactile feedback. In contrast to the RobHI, a remapping between the joints is less interesting due to the serial connection of the human leg joints.

The implementation of the robotic leg illusion by the Int2Bot mimics postural movements of the hidden human leg in sagittal plane while the subject stands close to it (see Figure 2 and [19], [25]). Mechanically the robotic system resembles the appearance and functionality of foot, shank, and thigh. The ankle and knee joint are actuated using DC motors [19]. To realize the imitation of human motions, those are measured with inertial measurement units attached to an interface orthosis which further integrates vibrotactile feedback [19], [26]. The control algorithms are implemented on a real-time controller that acquires the positions of the robot limbs by incremental encoders [19].

To match the anatomical properties of most participants, the segment lengths of shank and thigh can be varied [25]. For optical compliance, the hull of shop-window mannequin implies a more natural outer appearance and the robotic device is dressed with the same trousers as the subject [25].

Fig. 2. Setup of RobLI as proposed in [25].

III. REQUIREMENT ANALYSIS

The design requirements of the RobHI/RobLI setups from [22] and [25] are studied considering rubber limb research due to the initial stage of robotic experiments.

A. Methods to determine and compare design requirements

To systematically determine requirements, assess their specifications, and compare their implementations, the authors are grouped by discipline and city: group E comprises the engineers (Beckerle and De Beir) and group P the psychologists (Caspar and Schürmann). The interdisciplinary groups B and D are composed of the authors from Brussels (Caspar and De Beir) and Darmstadt (Beckerle and Schürmann). Hence, the study provides the possibility to consider different views of disciplines and research groups through comparing the ratings of the four authors. Their complementary perspectives are ensured by their backgrounds: Beckerle (human-centered mechatronics/robotics), Caspar (neuropsychology/cognitive neurosciences, De Beir (electromechanical engineering/neuropsychology), and Schürmann (psychology/human sensorimotor integration. All authors have experience in artificial limb illusions experiments [21], [26].

The requirement analysis process is performed as follows:

- Step 1: Brainstorming and clustering of design requirements by discussion and consensus of group E.
- Step 2: requirements are specified by groups B and D.
- Step 3: requirement list is refined by group E.
- Step 4: requirements are ranked and their similarities and differences are discussed by groups B and D.
- Step 5: both requirement comparison results are fused by discussion and consensus of group E, global design implications are determined.
- Step 6: psychological interpretation by group P.

B. Clusters and criteria of design requirements

The requirements and clusters (Clust.) determined in steps 1 to 3 are presented in Table I. The clusters are: setup characteristics, robot mechanics, actuation, and control as well as human motion acquisition and others.

Setup characteristics comprise overall properties like the distance between human and robotic device or how the real human limb is hidden. Additionally, anatomical plausibility, the option to transport the setup, and visual appearance of the robotic limbs are considered. Further design issues can be the possibility to structure the experimental procedure in order to avoid effects caused by the experimenter and variability as well as its reliability and robustness.

The clusters directly concerning the robotic device itself are mechanics (degrees of freedom, range of motion, adjustability to human body geometry, weight), actuation (speed, torque/force, power, size and weight, acoustics), and control (spatial accuracy, temporal delay, robot position sensing, no robot motion if human is resting, possibility of delayed/random motion, motion-mapping). Robot control is directly connected to the cluster about human motion acquisition (acq.) that comprises the tracking accuracy (spatial) and delays (temporal) as well as measurement noise and size/weight of the measurement system. Other aspects include the implementation of user-feedback and the price.

C. Analysis results

Besides determining and clustering the criteria, analysis steps 1 to 3 specify the RobHI and RobLI requirements. Those and their comparison in steps 4 and 5 are included in Table I. If the authors judged a single criterion to be similar or different between RobHI and RobLI, this is indicated by background color: gray (similar) and white (different). Regarding criteria that are marked by an asterisk, the members of group E developed consensus based on a previously different categorization by groups B and D.

The results show a high similarity of the requirements since $71,4\%$ are assessed to be similar and $28,6\%$ to be different. Despite the different perspectives of the rating groups, a high percentage of agreement can be observed ($78,6\%$). In all cases without initial agreement, a consensus was found by clarifying the difference between the requirement definition and its specific value/characterization.

IV. DISCUSSION AND IMPLICATIONS

The results in Table I are discussed regarding criteria similarities/differences and importance subsequently.

A. Similarities and differences

Very similar requirements are found regarding setup characteristics. Distance is important for RobHI and RobLI and even quantified similarly with values below $0.3m$. An important difference is observed regarding hiding the real limb which seems to be much simpler in RobHI since the real leg needs to take over body weight in RobLI. Yet, hiding is essential for creating both illusions. Requirements on plausibility and visual appearance are similar due to the importance of human-like appearance and position/orientation [33], [26]. Anatomical plausibility might depend on uncertainties in limb location perception [40] which could be higher for the legs due to increased distance which might further lower its impact on the illusion. Transportable solutions for experiments are seen similarly helpful but not crucially important. Software-controlled experiments are essential to reduce variability and bias caused by the human experimenter since computer-generated instructions can synchronize human actions with experiment and thus potentially increase result quality. Reliability and robustness are rated similar as well since they need to be sufficient for focusing on the experiment but not on commercial product level.

The mechanical requirements on degrees of freedom and their range of motion are similar. Both need to meet the task without being ideally natural. Hence, both have average priority since subjects might adjust to the motion capabilities of the robotic device. In RobHI, the dexterity of the hand should be considered. Although being rated to be not too important, another difference is found in the adjustability of the robotic limb to human body geometry: this might be

TABLE I

COMPARISON OF THE DESIGN REQUIREMENTS OF ROBHI AND ROBLI SETUPS AS PROPOSED IN [22], [25].

Clust.	Criterion	RobHI	RobLI
Setup characteristics	Distance human/robotic limb	Max 27.5cm [32] Importance of the position of both real and fake hand relatively to the body [33]	0.1 to 0.2 m [25], [32], illusion strongly depends on distance [26].
	Hiding the real human limb	Robot hand placed next/below human hand, separated by rigid structure. Human arm covered by fabric.	Frame with fabric, hiding the leg during squats is challenging due to human body weight bearing [26].
	Anatomical plausibility	Position of the fake hand should be anatomically plausible with respect to the body [33]. The angle between the two hands should be similar [34] .	Size of the robotic device should be adapted to population by mechanics [25], orientation expected to be relevant.
	Transportable for experiments*	RobHI and experimental setup are required to be transportable [22].	Transportable solution required [25].
	Visual appearance of fake limb	Ideally similar to human hand. But the illusion is quite robust and can resist to small visual variations [35].	Selection of shape, laterality, and cladding to support human-likeness by hiding technical parts [25], [36].
	Software-controlled experimental conditions	Computerized control to avoid bias through the experimenter and remove variability.	Digital control that minimizes variability and bias through the experimenter.
	Reliability and robustness	Is an issue due to frequent use by (non-)experts.	Should be as good as possible to focus on BSI research.
Robot mechanics	Required degrees of freedom*	Underactuated flexion for each finger is sufficient [22]. Thumb is rarely used.	Ankle and knee, limited to sagittal plane, both simple rotational joints [25]
	Range of motion*	Complete flexion/extension for each finger. Small flexion should be possible to push a buttons [24].	90 for the ankle (compensates for missing toe joints) and 180 for the knee [25]
	Adjustability to human body geometry	The illusion is very robust therefore a standard dimension can be used. Different sizes need to be used for the sensory glove.	Variable adaptation to subjects body geometries (5th to 95th percentile) [25], [37]. Practical feasibility and usefulness to be determined.
	Weight	Light fingers reduce inertia, bouncing and allow faster motion [22].	Lightweight to minimize actuation effort and human-like size [25].
Robot actuation	Speed*	High speed with minimum delays (faster than robotic hand commercially available). The hand should accurately reproduce finger flexion performed up to 3Hz.	High speed with minimum delay (to accurately track squat motions that are performed by humans with about 1Hz) [25], [38].
	Torque/force	Participants can be in direct contact with the robotic device (they often touch it by curiosity). Therefore low torque and/or compliant actuation is required for safety.	Depending on the loads due to the robot mass and rigid actuation for good position tracking [25].
	Power	Low voltage is advised for safety concerns. Sensors of the glove can induce noise on other sensors used by psychologist. Electromagnetic disturbance is only a concern when using EEG.	Low at the knee since motor needs to be moved by the ankle actuator, high for the ankle motor to reduce loading for better acoustics (hidden below ground) [25]. Electromagnetic disturbances to be considered for psycho-physiological measures.
	Size and weight	No specific requirements on motor size and weight when using tendons [22]. Small actuators if they are directly integrated in the fingers [23].	Lightweight to reduce motor loading, limitations in knee width essential for bevel gearbox [25].
	Acoustics	Closed box and rubber damping to reduce motor acoustic noise. Acoustic noise might be a issue, but no research has been conducted in it yet.	Reduced load, actuator dimensioning, belt drive, and housing of components to avoid/ reduce acoustic disturbance [25].
Robot control	Spatial control accuracy*	Low. Position shift is acceptable if it is constant [22].	Similar amplitude and motions up to 1Hz [25].
	Temporal control delay	Needs to remain small, constant and quantified [22]	As low as possible [25]. Not higher than 0.1s including acquisition delay [39].
	Robot position sensing*	Position sensing is performed on the motors. No additional sensors in the fingers are required.	Required (usually less important due to higher accuracy than obtained in human motion acquisition) [25].
	No robot motion if human at rest.	No trembling movements are absolutely required. noise on the movements clearly breaks the illusion.	No trembling movements. Smooth motions required.
	Possibility of delayed /random motion	possibility to program precisely between real and robotic finger (for each finger independently.) Possible to add fixed and/or random sequence during the experiment (dissociated from participant motion) [21]	Delay should be programmable [25] and joint motions might be randomized (both rather simple if digital control is applied).
	Motion-mapping	Possibility to remap robotic and real fingers during the experiment [21].	Not applicable since only one leg is present/ considered and both move the same way in squats.
Human motion acq.	Spatial tracking accuracy*	Position of real and fake fingers can differ [22], [34].	Rather high to yield congruent motions [25], [28].
	Temporal tracking delay	Delays need to be very small as they cancel the illusion. The delays should be constant an precisely measured	As low as possible since delays add up with those induced by motion control [25], [28]. Not higher than 0.1s including robot control delay [39]
	Measurement noise	Relevant if using optical tracking. Less an issue with sensory glove using flex sensor	Highly relevant for optical tracking [28], could still be an issue considering IMUs but less relevant [25].
	Size and weight (of components attached to human subject)	The tracking device should not interfere with the hand motion.	Should not disturb motions [25] but contact-free solution is not a hard requirement [19], [26].
Other	User-feedback (further perceptual channels)	Vibrotactile and acoustic might be considered.	Vibrotactile through vibration motors to investigate impact on multisensory integration [19].
	Price	Affordable price allows many labs to conduct research.	Low.

more important for the leg due to its dimensions and possible reference-mismatches (consider [33]). Both designs benefit from light weight design to use of small actuators.

Actuation speed is basically similar since RobHI and RobLI both require human-like motions. Yet, the particular values might be increased for the RobHI due to the higher speeds of hand motions. An important difference is found for the force/torque requirements. While both setups need low values to avoid harming human subjects in the case of contact, a certain torque level is required to enable weight bearing and balancing in RobHI. Low power actuators are similarly demanded to avoid interference with the environment, avoid disturbances of appearance, and to additionally decrease power requirements by a lean robot design. This is in line with acoustic requirements since direct disturbances of the illusion should be avoided in RobHI and RobLI. Yet, acoustics could hypothetically influence the multisensory integration that creates the illusion.

The requirements of control and human motion acquisition are connected since they add up to system accuracy and delay. While spatial issues are not crucial to the RobHI, they might be in RobLI. As mentioned above, the whole body is moving during squats which might create a difference in referencing in addition to effects caused by the mere size of the leg. Contrary, delay requirements are similar for RobHI and RobLI since low delay is essential to facilitate the illusion. It would be beneficial for experimental design if the delay value could be quantified. Robot position sensing is rated to be different since RobHI might need higher accuracy. However, such sensing is very precise anyway and thus less important than motion acquisition accuracy. An important requirement in both cases is that no robot motion occurs when the human subject is at rest since such could disturb the illusion [22]. Further, the possibility to perform delayed or random motions represents an important independent variable. It might even be strictly required depending on the test design. Yet, a remapping of joint motions only makes sense between the fingers since the leg has less degrees of freedom and those are hardly exchangeable due to their serial connection. Regarding human motion acquisition, requirements concerning measurement noise and component size/weight are similar: noise might be a more important issue in optical tracking while body-attached sensors should not affect the illusion. Body-attached sensing seems to be uncritical due to sensors such as inertial measurement units and the fact that the body might need to be contacted for vibrotacticle feedback anyway. The latter is an interesting aspect to investigate how the fidelity of the illusion is influenced by haptic feedback. Economically, RobHI and RobLI aim at sufficient low-cost solutions since they are used in research where funding might be limited.

B. Importance for design decisions

Five criteria were ranked to be most important in step 5 by group E: hiding the real limb, anatomical plausibility, visual appearance, temporal delay, and software-controlled experimental conditions. Considering delay of control and human motion acquisition as an overall system value, those all represent setup characteristics that are either tightly related to the stimulation/disturbance of the illusion itself or its systematic investigation. This suggests, that particular requirements are only relevant if they globally impact the psychological effect. This is supported by the high but not top-ranked criteria which comprise acoustics and the suppression of robotic motion during human rest which can also be interpreted as system properties influencing illusion quality. Regarding temporal delay, a constant and especially a quantifiable value might be of high importance.

C. Psychological interpretation

Limb illusions occur because of multisensory integration of vision, touch, and proprioception. The high-ranked design requirements appear to be appropriate in this context since they impact multisensory integration. The influence of factors like anatomical plausibility or temporal delay can in fact be understood in terms of a Bayesian integration process as showcased in [41]. Working towards a subjects inference of an underlying common cause between real and artificial limb stimulation, the established design requirements provide an intuitive explanation of an illusions success. It is interesting to note that the conditions that researchers have identified allow to create an illusion of body-ownership to healthy participants in only a couple of minutes, while it takes months for amputee patients to develop a perception of embodiment over the prosthesis due to neural plasticity [42]. Additionally, literature indicates that some subjects are non-responders in embodiment illusions [16]. These results suggest that focusing the high-ranked design requirements supports inducing of limb illusions for the majority of healthy subjects. The issue of non-responders and the extended time required by amputees to adapt their body schema need further investigation in terms of their impact on design requirements.

V. CONCLUSIONS

This paper systematically analyzes design requirements of robotic limbs that are used to experimentally explore human body schema integration. Robotic hand/leg illusion (RobHI/RobLI) setups can improve the understanding psychological fundamentals and their design requirements might be transferred to the development of the final robotic application. Yet, most experimental setups are rather proprietary and the corresponding development processes are unstructured.

To support engineering decisions, a structured and ranked list of requirements as well as design implications are determined in a comparative study by engineers and psychologists. It is found that setup characteristics concerning hiding the real limb, anatomical plausibility, visual appearance, temporal delay, and software-controlled experiments are most crucial and should receive highest priority. While requirement importance is mostly similar in RobHI and RobLI, particular aspects differ considerably, e.g., hiding the weight bearing leg in RobLI is very challenging. With such insights, this paper guides the design of future robotic experiments on body schema integration that maintain the validity and purpose of the traditional experiments.

Future works might consider more RobHI/RobLI setups to improve global applicability. Further, psychological experiments might be performed to substantiate the benefits in human body schema integration and identify which are the key modalities of the multisensory integration process.

REFERENCES

[1] A. Mayer, K. Kudar, K. Bretz, and J. Tihanyi, "Body schema and body awareness of amputees," *Prosthetics and Orthotics International*, vol. 32 (3), pp. 363 – 382, 2008.

[2] S. Gallagher and J. Cole, "Body Schema and Body Image in a Deafferented Subject," *Journal of Mind and Behavior*, vol. 16, pp. 369 – 390, 1995.

[3] P. H. Holmes and C. Spence, "The body schema and the multisensory representation(s) of peripersonal space," *Cognitive Processing*, vol. 5 (2), pp. 94 – 105, 2004.

[4] Y. Rybarczyk, D. R. Mestre, E. Colle, and P. Hoppenot, *Sensori-motor appropriation of an artefact: a neuroscientific approach*. INTECH Open Access Publisher, 2012.

[5] L. Cardinali, F. Frassinetti, C. Brozzoli, C. Urquizar, A. C. Roy, and A. Farnè, "Tool-use induces morphological updating of the body schema," *Current Biology*, vol. 19, no. 12, pp. R478–R479, 2009.

[6] A. Maravita and A. Iriki, "Tools for the body (schema)," *Trends in cognitive sciences*, vol. 8, no. 2, pp. 79–86, 2004.

[7] M. Botvinick and J. Cohen, "Rubber hands 'feel' touch that eyes see," *Nature*, vol. 391, p. 756, 1998.

[8] M. Flögel, K. T. Kalveram, O. Christ, and J. Vogt, "Application of the rubber hand illusion paradigm: comparison between upper and lower limbs," *Psychological Research*, vol. 2, pp. 1 – 9, 2015.

[9] O. Christ, A. Elger, K. Schneider, P. Beckerle, J. Vogt, and S. Rinderknecht, "Identification of haptic paths with different resolution and their effect on body scheme illusion in lower limbs," *Technically Assisted Rehabilitation*, 2013.

[10] M. Flögel, P. Beckerle, and O. Christ, "Rubber hand and rubber foot illusion: a comparison and perspective in rehabilitation," *Clinical Neurophysiology*, vol. 125 (S1), p. 113, 2014.

[11] B. Lenggenhager, T. Tadi, T. Metzinger, and O. Blanke, "Video ergo sum: manipulating bodily self-consciousness," *Science*, vol. 317 (5841), pp. 1096 – 1099, 2007.

[12] J. E. Aspell, B. Lenggenhager, and O. Blanke, "Keeping in touch with one?s self: Multisensory mechanisms of self-consciousness," *PLoS ONE*, vol. 4 (8), p. e6488, 2009.

[13] A. Maselli and M. Slater, "The building blocks of the full body ownership illusion," *Frontiers in human neuroscience*, vol. 7, p. 83, 2013.

[14] R. Bekrater-Bodmann, J. Foell, M. Diers, and H. Flor, "The perceptual and neuronal stability of the rubber hand illusion across contexts and over time," *Brain Research*, vol. 1452, pp. 130 – 139, 2012.

[15] V. I. Petkova, H. Zetterberg, and H. H. Ehrsson, "Rubber hands feel touch, but not in blind individuals," *PloS one*, vol. 7, no. 4, p. e35912, 2012.

[16] O. Christ and M. Reiner, "Perspectives and possible applications of the rubber hand and virtual hand illusion in non-invasive rehabilitation: Technological improvements and their consequences," *Neuroscience and Biobehavioral Reviews*, 2014.

[17] M. Hara, P. Pozeg, G. Rognini, T. Higuchi, K. Fukuhara, A. Yamamoto, T. Higuchi, O. Blanke, and R. Salomon, "Voluntary self-touch increases body ownership," *Frontiers in Psychology*, vol. 6, 2015.

[18] M. Hara, H. Nabae, A. Yamamoto, and T. Higuchi, "Effect of force feedback on rubber hand illusion," in *IEEE International Conference on Systems, Man, and Cybernetics*, 2013.

[19] P. Beckerle, F. Schültje, J. Wojtusch, and O. Christ, "Implementation, Control and User-Feedback of the Int^{2}Bot for the Investigation of Lower Limb Body Schema Integration," in *IEEE International Symposium on Robot and Human Interactive Communication*, 2014.

[20] H. H. Ehrsson, B. Rosén, A. Stockselius, C. Ragnö, P. Köhler, and G. Lundborg, "Upper limb amputees can be induced to experience a rubber hand as their own," *Brain*, vol. 131, no. 12, pp. 3443–3452, 2008.

[21] E. A. Caspar, A. de Beir, P. A. Magalhães Da Saldanha da Gama, F. Yernaux, A. Cleeremans, and B. Vanderborght, "New frontiers in the rubber hand experiment: when a robotic hand becomes ones own," *Behavior Research Methods*, vol. 47 (3), pp. 744–755, 2015.

[22] A. De Beir, E. A. Caspar, F. Yernaux, P. A. Magalhães Da Saldanha da Gama, B. Vanderborght, and A. Cleermans, "Developing new frontiers in the rubber hand illusion: Design of an open source robotic hand to better understand prosthetics," in *IEEE International Symposium on Robot and Human Interactive Communication*, 2014.

[23] R. Romano, E. Caffa, A. Hernandez-Arieta, P. Brugger, and A. Maravita, "The robot hand illusion: Inducing proprioceptive drift through visuo-motor congruency," *Neuropsychologia*, vol. 70, pp. 414 – 420, 2015.

[24] E. A. Caspar, A. Cleeremans, and P. Haggard, "The relationship between human agency and embodiment," *Consciousness and Cognition*, vol. 33, pp. 226 – 236, 2015.

[25] P. Beckerle, O. Christ, J. Wojtusch, J. Schuy, K. Wolff, S. Rinderknecht, J. Vogt, and O. von Stryk, "Design and control of a robot for the assessment of psychological factors in prosthetic development," in *IEEE International Conference on Systems, Man and Cybernetics*, 2012.

[26] T. Schürmann, P. Overath, O. Christ, J. Vogt, and P. Beckerle, "Exploration of lower limb body schema integration with respect to body-proximal robotics," in *IEEE International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow*, 2015.

[27] P. Pozeg, G. Galli, and O. Blanke, "Those are your legs: The effect of visuo-spatial viewpoint on visuo-tactile integration and body ownership," *Frontiers in psychology*, vol. 6, 2015.

[28] F. Schültje, P. Beckerle, M. Grimmer, J. Wojtusch, and S. Rinderknecht, "Comparison of Trajectory Generation Methods for a Human-Robot Interface based on Motion Tracking in the Int^{2}Bot," in *IEEE International Symposium on Robot and Human Interactive Communication*, 2014.

[29] O. Christ, P. Beckerle, J. Preller, M. Jokisch, S. Rinderknecht, J. Wojtusch, O. von Stryk, and J. Vogt, "The rubber hand illusion: Maintaining factors and a new perspective in rehabilitation and biomedical engineering?" *Biomedical Engineering*, vol. 57(S1), pp. 1098 – 1101, 2012.

[30] T. Dummer, A. Picot-Annand, T. Neal, and C. Moore, "Movement and the rubber hand illusion," *Perception*, vol. 38, pp. 271–280, 2009.

[31] A. Kalckert and H. H. Ehrsson, "Moving a rubber hand that feels like your own: A dissociation of ownership and agency," *Frontiers in Human Neuroscience*, vol. 6 (40), 2012.

[32] D. M. Lloyd, "Spatial limits on referred touch to an alien limb may reflect boundaries of visuo-tactile peripersonal space surrounding the hand," *Brain and Cognition*, vol. 64, pp. 104–109, 2007.

[33] C. Preston, "The role of distance from the body and distance from the real hand in ownership and disownership during the rubber hand illusion," *Acta psychologica*, vol. 142, no. 2, pp. 177–183, 2013.

[34] M. Costantini and P. Haggard, "The rubber hand illusion: sensitivity and reference frame for body ownership," *Consciousness and cognition*, vol. 16, no. 2, pp. 229–240, 2007.

[35] A. Haans, W. A. IJsselsteijn, and Y. A. de Kort, "The effect of similarities in skin texture and hand shape on perceived ownership of a fake limb," *Body Image*, vol. 5, no. 4, pp. 389–394, 2008.

[36] M. Tsakiris, M. R. Longo, and P. Haggard, "Having a body versus moving your body: Neural signatures of agency and body-ownership," *Neuropsychologia*, vol. 48, pp. 2740–2749, 2010.

[37] H. Greil, "Köpermaße 2000: Aktuelle Perzentilwerte der deutschen Bevölkerung im jungen Erwachsenenalter," *Brandenburgische Umwelt Berichte*, 2001.

[38] R. F. Escamilla, "Knee biomechanics of the dynamic squat exercise," *Medicine & Science in Sports & Exercise*, vol. 33, pp. 127–141, 2001.

[39] O. Christ, C. Weber, I. Borchert, and H. Sorgatz, "Dissonance between visual and proprioceptive information as a moderator in experimental pain," *Journal of Rehabilitation Medicine*, vol. 43(9), p. 836, 2011.

[40] R. J. van Beers, A. C. Sittig, and J. J. Denier van der Gon, "The precision of proprioceptive position sense," *Experimental Brain Research*, vol. 122 (4), pp. 367 – 377, 1998.

[41] M. Samad, A. J. Chung, and L. Shams, "Perception of body ownership is driven by bayesian sensory inference," *PLoS ONE*, vol. 10 (2), p. e0117178, 2015.

[42] F. De Vignemont, "Embodiment, ownership and disownership," *Consciousness and Cognition*, vol. 20 (1), pp. 82 – 93, 2011.